



**US Army Corps  
of Engineers®**  
Engineer Research and  
Development Center

**ERDC**  
INNOVATIVE SOLUTIONS  
for a safer, better world

*ERDC's Center-Directed Research Program*

## **Ground-Penetrating-Radar Profiles of Interior Alaska Highways**

**Interpretation of Stratified Fill, Frost Depths, Water Table, and Thaw Settlement over Ice-Rich Permafrost**

Steven A. Arcone and Kevin Bjella

August 2016

**The U.S. Army Engineer Research and Development Center (ERDC)** solves the nation's toughest engineering and environmental challenges. ERDC develops innovative solutions in civil and military engineering, geospatial sciences, water resources, and environmental sciences for the Army, the Department of Defense, civilian agencies, and our nation's public good. Find out more at [www.erdc.usace.army.mil](http://www.erdc.usace.army.mil).

To search for other technical reports published by ERDC, visit the ERDC online library at <http://acwc.sdp.sirsi.net/client/default>.

# Ground-Penetrating-Radar Profiles of Interior Alaska Highways

Interpretation of Stratified Fill, Frost Depths, Water Table, and Thaw Settlement over Ice-Rich Permafrost

Steven A. Arcone

*U.S. Army Engineer Research and Development Center (ERDC)  
Cold Regions Research and Engineering Laboratory (CRREL)  
72 Lyme Road  
Hanover, NH 03755-1290*

Kevin Bjella

*U.S. Army Engineer Research and Development Center (ERDC)  
Cold Regions Research and Engineering Laboratory (CRREL)  
Alaska Projects Office  
Building 4070, 9th Street  
Fort Wainwright, AK 99703*

Final Report

Approved for public release; distribution is unlimited.

Prepared for The ERDC Director's Office  
3909 Halls Ferry Road  
Vicksburg, MS 39180-6199

Under ERDC Center-Directed Research, "Integrated Technologies for Delineating Permafrost and Ground-State Conditions"

## Abstract

In early spring 2014, we recorded ground-penetrating-radar (GPR) profiles along several highways in interior Alaska to determine present and potential damaging thaw settlement, which could help site and design infrastructure in permafrost terrains. We used GPR pulses centered near 100, 150, and 320 MHz. Comparative profiles of electrical resistivity, historical GPR profiles, and limited borehole information aided interpretations. Beneath the Elliott Highway, Goldstream Road, and the Old Steese Highway, construction fill was recognized by its stratification; and frost depth and water-table horizons were recognized by phase attributes of the reflected pulse, as dictated by dielectric permittivity contrasts, relative depths, and continuity. Undulating fill stratification indicated thaw settlement, caused by melting of buried ice. We interpreted various stratigraphic folds to represent cases of active, recent, remediated and historical settlement. A section along the Tok Cutoff Road revealed the top and bottom of massive ice within glacial moraine. Signal penetration was greatly reduced beneath the water table, and the permafrost table was not detected. This information is valuable for highway maintenance and planning of new construction, especially in remote locations where information on permafrost and ice features are limited.

# Contents

<b>Abstract .....</b>	<b>ii</b>
<b>Illustrations .....</b>	<b>iv</b>
<b>Preface .....</b>	<b>vii</b>
<b>1 Introduction.....</b>	<b>1</b>
1.1 Background .....	1
1.2 Objective.....	2
1.3 Approach .....	2
<b>2 System.....</b>	<b>4</b>
2.1 Antennas .....	4
2.2 Data acquisition and handling.....	5
2.3 Depth and thickness interpretation and estimated error.....	6
2.4 DC resistivity .....	6
<b>3 Sites .....</b>	<b>7</b>
<b>4 Results .....</b>	<b>8</b>
4.1 Elliott Highway.....	8
4.2 Goldstream Road.....	12
4.3 Tok Cutoff Road .....	18
4.4 Old Steese Highway .....	20
<b>5 Discussion and Conclusions .....</b>	<b>23</b>
<b>References .....</b>	<b>24</b>
<b>Report Documentation Page</b>	

# Illustrations

## Figures

- 1 A GSSI Model 5106A “200 MHz” antenna unit in tow on a metal-free sled and on a high-density polyethylene ( $\epsilon = 2.4$ ) platform. The actual center frequency of pulses received was closer to 150 MHz. The Model 5103 “400 MHz” unit is of identical design but smaller.....4
- 2 (A) Transmitted pulse shape and (B) its inversion after reflection from an interface between material of relatively lower permittivity above and higher below (e.g., frozen soil/unfrozen soil). The pulse does not invert if the higher permittivity material is above the interface. These are also the waveforms for thin embedded layers of relatively low permittivity (A) and relatively high (B). In the profiles, positive half cycles are white; and negative are black .....5
- 3 Location map of our road radar sites. The Elliott Highway starts in Fox, just north of Fairbanks. Goldstream Road is north of Fairbanks. Tok Cutoff Road runs from just north of Glenallen to Tok Junction. All sites are considered to be in interior Alaska and within the discontinuous permafrost zone.....7
- 4 (A) 1958 surficial geology map (Péwé 1958) showing that the Elliott (superimposed 1.8 km long red line) is along a section of frozen silt. The highway was realigned and widened since 1958. (B) Google Earth image of the present day highway. The Elliott starts at Fox; the yellow line is 1.86 km long. (C) Google Earth perspective view showing that the highway is in a valley .....8
- 5 A 320 MHz profile of the first 1860 m of the Elliott Highway, recorded 4 April 2014. The start is at the truck weigh station at Fox. The speckled blue bars show where the road was patched during summer 2014 because of thaw settlement. Yellow arrows indicate the bottom of seasonal frost, and the turquoise arrows indicate the water table. The seasonal frost delineates the fill. HF and AHF labels are below the appropriate folding features, caused by selective thaw settlement above ice deep within the permafrost. The water table often sits right on the permafrost because there is no deeper horizon. There are no hyperbolic diffraction signatures to indicate massive ice. The photos are of the culverts, whose responses are within the dashed circles. The stratigraphic note at the lower left is from borehole records .....9
- 6 (A) Detail of a deeply frozen section recorded with the larger, 150 MHz antenna unit, showing the inability of lower frequency and 8× more power to penetrate any deeper. The underlying material is likely ice-rich loess. AHF indicates anharmonic folding above. (B) Migration for  $\epsilon = 5$  of the culvert (shown in inset) response at 1798 m distance (within dashed circle). The collapse of the hyperbolic diffraction to just a few traces justifies the use of this dielectric constant. The placement of the migrated diffraction shows that our GPS may have been misaligned by about 4 m .....10
- 7 The key to interpretation of the presence of massive or concentrated ice. HF shows harmonic folds, in which all folds are concentric. This would occur if the folds are a reaction to only recent sagging so that the fold in the upper few layers projects down through the GPR column. AHF shows anharmonic folds, in which the folds deepen with depth, which means they are old and indicate long progressing settlement.....11
- 8 The OhmMapper resistivity profile (2.5 m electrode spacing) along the Elliott Highway. Red to dark red indicates high ice content. The maximum profile depth

is 4.6 m, similar to the profile horizons. The highest resistivity is at 1000–1220 m (deepest gravel fill), 1250–1500 m (thaw settlement under folding), and 1700–1800 m where no horizons greater than 1 m suggest high attenuation (e.g., barely frozen, such as ice-rich silt, or thaw). A borehole at 1752 shows frost to 4.3 m, wet silt to 5.9 m, then frozen silt, which is consistent with this figure because it shows high resistivity to a 4.6 m depth .....12

9 (A) Another 150 MHz GPR section showing about 10 m penetration into the underlying schist. There is no clear frost depth horizon, but there are hints (arrows) that it dives deeper within the schist. (B) A photo showing schist exposed above the road from 2200 to 2280 m. The Péwé map (Fig. 4) shows a 30° dip to the south for the schistosity, and with strike (orientation of the dipping planes) across the road. The profile shows 21°. (C) An OhmMapper profile showing high resistivity from 2180 to 2300 m, right over the schist .....12

10 (A) 6.6 km of Goldstream Road, starting 100 m past the fire station. The start is approximately at the X mark in the geologic map (B) of Péwé (1958), and the transect is within the rectangular box. Qsu (*pink area*) means undifferentiated quaternary silt .....13

11 150 MHz profile sections between 840 and 1440 m along Goldstream Road, recorded 9 April 2014. *Yellow arrows* indicate the frost depth, and *turquoise arrows* indicate the water table. Folds indicate thaw settlement. Old thaw settlement repair (OSR) occurs where folds do not continue to the surface. Conduits (C) are indicated by hyperbolic diffractions .....14

12 A 150 MHz profile section between 1700 and 2120 m along Goldstream Road, recorded 9 April 2014. *Yellow arrows* indicate the frost depth, and *turquoise arrows* indicate the water table. Folds indicate thaw settlement. Old thaw settlement repair (OSR) occurs where folds do not continue to the surface. Conduits (C) are indicated by hyperbolas .....15

13 Selected 150 MHz profile sections between 2340 and 3020 m along Goldstream Road, recorded 9 April 2014. *Yellow arrows* indicate the frost depth, and *turquoise arrows* indicate the water table. Folds indicate thaw settlement. Old thaw settlement repair (OSR) occurs where folds do not continue to the surface. Unrepaired thaw settlement (UTS) is indicated by folds that continue to the surface. Conduits (C) or clusters of conduits are indicated by hyperbolas .....16

14 Selected 150 MHz profile sections along the first 3.3 km of Goldstream Road, recorded 9 April 2014. *Yellow arrows* indicate the frost depth, and *turquoise arrows* indicate the water table. Folds indicate thaw settlement. Old thaw settlement repair (OSR) occurs where folds do not continue to the surface. Unrepaired thaw settlement (UTS) is indicated by folds that continue to the surface. Conduits (C) or clusters of conduits are indicated by hyperbolas .....17

15 Selected 150 MHz profile sections along the first 3.3 km of Goldstream Road, recorded 9 April 2014. *Yellow arrows* indicate the frost depth, and *turquoise arrows* indicate the water table. Folds indicate thaw settlement. Old thaw settlement repair (OSR) occurs where folds do not continue to the surface. Unrepaired thaw settlement (UTS) is indicated by folds that continue to the surface. Conduits (C) or clusters of conduits are indicated by hyperbolas. The lower profile shows contact of the water table to the frozen layer .....18

16 (A) An image from 9 April 2013 of the section of Tok Highway that has been repeatedly repaired since at least 1997. Arrows indicate black patches where thaw settlement has been repaired. (B) Detail of the area (indicated by *red arrow* in A) discussed in this report .....19

17 (A) A 280 MHz profile of Tok Cutoff Road recorded 20 March 1998 over an area of thaw settlement, shown in Fig. 5 (red arrow). A layer of insulating Styrofoam (Blue Board) sits atop this ice, which makes the reflection waveform white–black–white (insert; arrows points to where it occurs) as if it came from a wet surface. (B) A 97 MHz profile of same section showing complicated massive ice and melting. The massive ice in (B) now has a black–white–black band (*left* waveform insert), which is correct for solid ice under frozen sand and gravel and Blue Board too thin to change the waveform polarity. A massive ice horizon also occurs at the far right. The strong white–black–white banded horizons at the center (*center insert*) are likely meltwater draining off this massive ice.....20

18 (A) A section of the Old Steese Highway going N–S profiled August 2013. The distance from Springwater to Little Fox is 250 m and 1350 m to McGrath Road. The section lies entirely within the pink Qsu (Quaternary undifferentiated silt) unit of Péwé (1958) that resides within the box in (B).....21

19 A 150 MHz profile of a section of the Old Steese Highway going N–S and recorded 9 August 2013. The black–white–black horizon (*turquoise arrow*) means thaw over frozen. The  $\varepsilon_r = 7.8$  is the average for several conduit diffractions (*yellow arrows* at 325, 545, and 628 m), which are not discernible because of the horizontal compression used for display, and indicates well-drained sands and gravel. Diffractions generated within the nadir of a dip were not considered for interpretation of relative dielectric permittivity .....22

## Preface

This study was conducted for the Engineer Research and Development Center's (ERDC) Center-Directed Research Program under the project titled "Integrated Technologies for Delineating Permafrost and Ground-State Conditions." The technical monitor was Kevin Knuuti, Technical Director, ERDC Cold Regions Research and Engineering Laboratory (CRREL).

The work was performed by Dr. Steven Arcone (Signature Physics Branch, Dr. Loren Wehmeyer, Acting Chief) and Kevin Bjella (Force Projection and Sustainment Branch, Dr. Sarah Kopczynski, Acting Chief), U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL). At the time of publication, Dr. Loren Wehmeyer was Chief of the Research and Engineering Division. The Deputy Director of ERDC-CRREL was Dr. Lance Hansen, and the Director was Dr. Robert Davis.

COL Bryan S. Green was the Commander of ERDC, and Dr. Jeffery P. Holland was the Director.



# 1 Introduction

## 1.1 Background

The most important maintenance problem facing paved highways within interior Alaska is degradation caused by thaw settlement. Permafrost at any depth is always ice rich and may even contain massive ice. Despite the insulation of its burial, this ice may be close to or at 0°C or may contain salts that depress its freezing point, thus allowing melting. As the meltwater diffuses through the porous silts and sand, the road surface sags, cracks, and severely degrades. All major highways in interior Alaska are afflicted with this problem, including local roads within Fairbanks and other communities.

With climate change and global warming, which now severely affects interior Alaska, thaw settlement is becoming more evident and may become active in areas previously unaffected. The main purpose of this report is to show that ground-penetrating radar (GPR) not only can detect the presence of thaw settlement but also can reveal whether or not it is a recent or ongoing issue. In addition, we show that GPR reveals the general structure of the seasonal frost and water tables, which are also road construction and maintenance issues.

GPR is a common geophysical method used for subsurface imaging of stratified geological formations and for finding utilities. GPR uses short pulses centered within the radio frequency spectrum, typically between 50 and 3000 MHz. The higher frequencies provide higher vertical resolution at the expense of penetration depth. The short pulses allow the main feature of GPR, which is vertical resolution—specifically, resolution (separation) of reflections from different interfaces. The reflections are caused by changes in electrical properties, as defined by the relative dielectric constant,  $\epsilon_r$ , of each material. Transitions from frozen to unfrozen and from wet to dry cause the strongest reflections, hence the utility of GPR in cold regions terrains. Antenna units are typically dragged along the ground surface, although much work has been done with airborne systems.

The term “road radar” generally refers to GPR surveys of pavement construction and uses high-resolution pulses centered above 1 GHz to depths

less than 1 m. Such high frequencies and the evenly layered structure of pavements and substrate allow remote inspection and determination of pavement thickness and of degradation, which is almost always caused by water infiltration. However, in permafrost regions such as interior Alaska, both seasonal frost heaving (due to refreezing of spring meltwater) and thaw settlement cause degradation. In interior Alaska, by late winter, graded and frozen sand and gravel affords more than 10 m of signal penetration at pulse spectra center frequencies below about 400 MHz. This penetration, the smooth and nearly flat remediated surface, and buried conduits that can be exploited for depth calibration present ideal conditions that allow GPR imaging of freeze–thaw structure and dynamics.

## **1.2 Objective**

Our objective was to obtain GPR profiles of several sections of roads along which thaw settlement has been an ongoing issue. The particular sections we discuss are along the Elliot and Old Steese Highways, Goldstream Road, and Tok Cutoff Road (where we imaged massive ice within the deep sand and gravel of a natural glacial moraine in 1997).

## **1.3 Approach**

For this study, we used pulses centered from about 100 to 320 MHz. We compared some of our data with concurrent galvanic electrical resistivity profiles and the presence of road patches, which indicate areas of remediation.

The first ever published use of GPR was to detect massive ice in permafrost (Bertram et al. 1972). Subsequently, GPR has been continually used to locate massive ice (Annan and Davis 1976; Davis et al. 1976; Pilon et al. 1992; Brandt et al. 2007), to profile the thickness of the seasonally frozen surface layer known as the active layer (Arcone and Delaney 1982; Arcone et al. 1998; Gacitua et al. 2010), to find subsurface water within permafrost (Arcone et al. 1992, 1998), and to generally assess variable conditions associated with permafrost (Pilon et al. 1992; Moorman et al. 2003). Most of its success in penetrating permafrost has been obtained in areas of floodplain alluvial sands and gravels (Delaney et al. 1990; Arcone et al. 1992, 1998), where penetration in ice-rich sands may have reached 80 m and up to 40 m in deeply frozen Antarctic moraine (Arcone et al. 2002). A

strength of the GPR method is that measurements can be made along potential road corridors and over or through existing pavements, gravels, or other substrates. As such, GPR is useful in helping to route and design roads and in investigating problem spots along established roads. A similar problem, but on a finer scale, is the design, construction, and maintenance of vertical infrastructure on permafrost. Typically, information from boreholes is used to site buildings; but drilling is costly and time consuming, and even tightly spaced drilling information can miss large (i.e., meters) ice features.

## 2 System

### 2.1 Antennas

We used a GSSI SIR3000 16-bit control unit and the GSSI bistatic Model 5103 “400 MHz” and Model 5106A “200 MHz” antenna units. After impedance loading by pavement contact, the center frequencies were about 320 and 150 MHz, respectively. We towed the antennas very close to the surface by using the polyethylene platform shown in Figure 1. The antenna height above the surface was 5.7 cm, which added 0.6 ns (nanoseconds) to the delay of subsurface events, accounting for the 2.54 cm of high-density polyethylene.

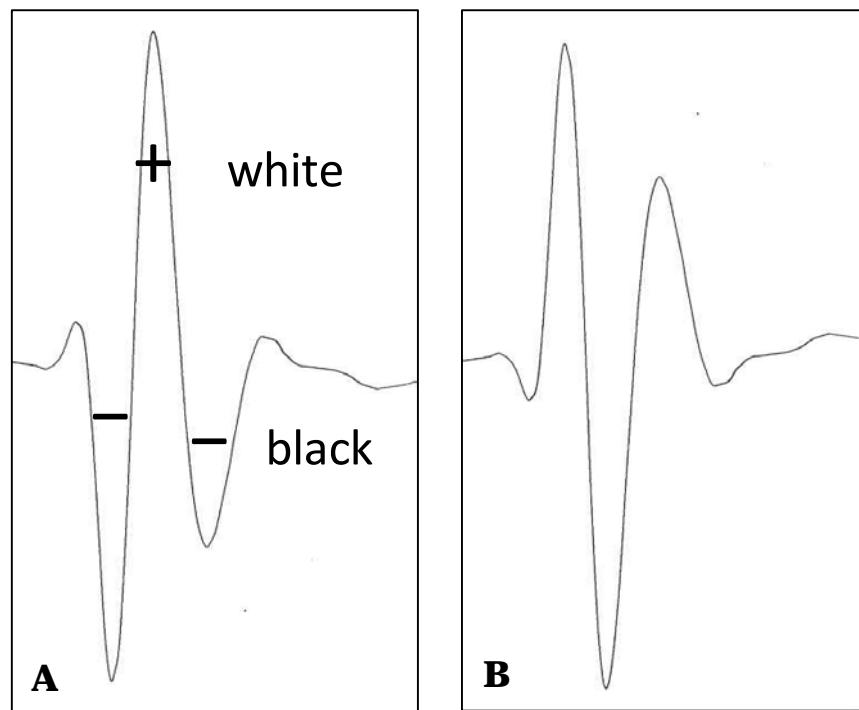
Figure 1. A GSSI Model 5106A “200 MHz” antenna unit in tow on a metal-free sled and on a high-density polyethylene ( $\epsilon = 2.4$ ) platform. The actual center frequency of pulses received was closer to 150 MHz. The Model 5103 “400 MHz” unit is of identical design but smaller.



Transmitted pulse waveforms for all antennas were mainly 1.5 cycles with a – + – polarity sequence for the sequential half cycles (Figure 2A). This sequence also occurs for a reflection from an interface between a relatively higher  $\epsilon_r$  medium (e.g., thaw) above a relatively lower  $\epsilon_r$  one (e.g., frozen) and from an isolated electrically thin (less than 0.4 wavelengths) layer with  $\epsilon_r$  lower than that of the surrounding matrix, such as a thin layer of remnant seasonally frozen material above and beneath unfrozen material. The opposite cases reverse the sequence. Pulse lengths in frozen sands and gravel ( $\epsilon_r = 5$ ) at 150 and 320 MHz are approximately 1.34 and 0.63 m,

respectively, giving a vertical interface resolution of 67 and 32 cm, respectively. The beamwidth along the antenna direction (to the side of the transects) is 53° measuring to the first null in the antenna directivity pattern. In the transect direction, the beamwidths are extremely wide (at least 70°).

Figure 2. (A) Transmitted pulse shape and (B) its inversion after reflection from an interface between material of relatively lower permittivity above and higher below (e.g., frozen soil/unfrozen soil). The pulse does not invert if the higher permittivity material is above the interface. These are also the waveforms for thin embedded layers of relatively low permittivity (A) and relatively high (B). In the profiles, positive half cycles are white; and negative are black.



The profiles provide stratigraphic sections in a line-intensity format with a nonlinear proportion between intensity and signal strength to give weaker signals greater amplification. Black bands represent negative amplitude half cycles, and white bands are positive. An isolated pulse has either black–white–black (− + −) or white–black–white (+ − +) banding.

## 2.2 Data acquisition and handling

We continuously recorded GPR profiles at time ranges of 175 ns at 320 MHz and 450 ns at 150MHz by using 1024 16-bit samples/trace with wide-band IIR (infinite impulse) filters. We used range gain that approximately

corrected for spherical-beam spreading loss; interfacial refraction and transmission losses made exact compensation impossible. We recorded the position every 50 or 100 m with nondifferential GPS to approximately  $\pm 2\text{--}3$  m precision. We normalized distance marks to compensate for varying profile speed and used a broadband IIR filter to alleviate high-frequency noise and low-frequency modulation. We applied automatic gain control to select segments to image faint horizons.

## 2.3 Depth and thickness interpretation and estimated error

We determined time zero for the GPR profiles by accounting for antenna separation (0.30 m for the 5106A; 0.15 m for the 5103 unit). We used the echo transit time formula,

$$d = ct / 2 n, \quad (1)$$

where  $n = \sqrt{\epsilon_r}$  is the real part of the refractive index and  $c = 0.3 \text{ m ns}^{-1}$ , to transform the round trip transit time,  $t$  (ns), into thickness (m) for separate sedimentary units. We estimate an error of  $\pm 1$  ns in picking any 150 MHz event and  $\pm 0.5$  ns for any 320 MHz event. An error of 1 ns translates to a depth error of 0.07 m in frozen material with  $\epsilon_r = 5$ . However, greater errors must result from inaccuracies in  $\epsilon_r$ . We used  $\epsilon_r = 5$  for the frozen sediments. We determined this by fitting model hyperbolic diffractions to those generated by culverts and then applying a Kirchhoff single-layer migration to find values that collapsed the diffractions to one or two traces or provided minimal convexity in the resulting signature. The matching routine gives about 6% precision in velocity and an error in  $\epsilon_r$  of less than 11% in the range of  $4.1 < \epsilon_r < 6.4$ . We checked these values where depths to buried conduits could be measured.

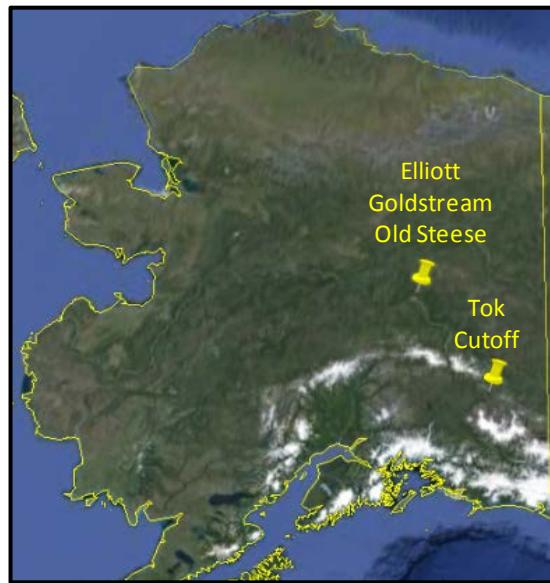
## 2.4 DC resistivity

We obtained resistivity profiles along the Elliott Highway by using the OhmMapper towed array, which has 5 electrodes spaced 2.5 m apart. The ground contact is capacitive rather than by emplaced electrodes. The system records data at a frequency of 10 Hz and averages many recordings. Further processing into models of layered resistivity and their display are done with company-supplied software. The maximum depth of penetration is approximately determined by the electrode spacing; and the processing showed a maximum of 7.35 m.

### 3 Sites

Figure 3 presents the sites we discuss. Site-specific maps are shown in the “Results” section. All sites were located within the discontinuous permafrost region of Alaska. The Elliott and Old Steese Highways and Goldstream Road are situated near Fairbanks within the extensive loess deposits, which are silts that are often frozen, especially on north facing hillsides and valleys. The ice may be segregated, meaning dispersed throughout the silt, or massive, meaning virtually solid ice formations. The Tok site was located at approximately mile 62 going north from the Richardson Highway. The highway there transects a large glacier moraine, likely emplaced when glaciers flowed north from Mt. Wrangle, whose closest glacier is about 40 km to the south.

Figure 3. Location map of our road radar sites.  
The Elliott Highway starts in Fox, just north of  
Fairbanks. Goldstream Road is north of  
Fairbanks. Tok Cutoff Road runs from just north  
of Glenallen to Tok Junction. All sites are  
considered to be in interior Alaska and within the  
discontinuous permafrost zone.



## 4 Results

### 4.1 Elliott Highway

Figure 4A shows the general surficial geologic setting of the Elliott Highway from where it starts at the truck weigh station in Fox and then for the ensuing 4 km. The highway section is within a valley filled with Quaternary undifferentiated and reworked silts, consisting mostly of quartz, feldspars, and micas, with little clay size content. The valley walls are exposed Birch Creek schist. Figure 4B shows the present alignment, and Figure 4C gives a perspective looking north and reveals that the valley walls are not steep.

Figure 4. (A) 1958 surficial geology map (Pewé 1958) showing that the Elliott (superimposed 1.8 km long red line) is along a section of frozen silt. The highway was realigned and widened since 1958. (B) Google Earth image of the present day highway. The Elliott starts at Fox; the yellow line is 1.86 km long. (C) Google Earth perspective view showing that the highway is in a valley.

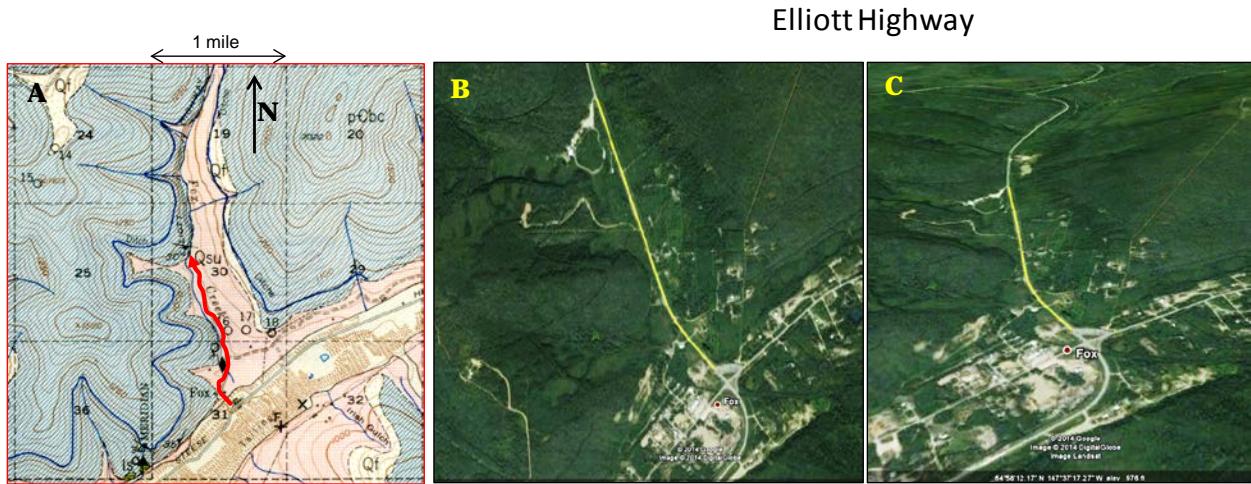
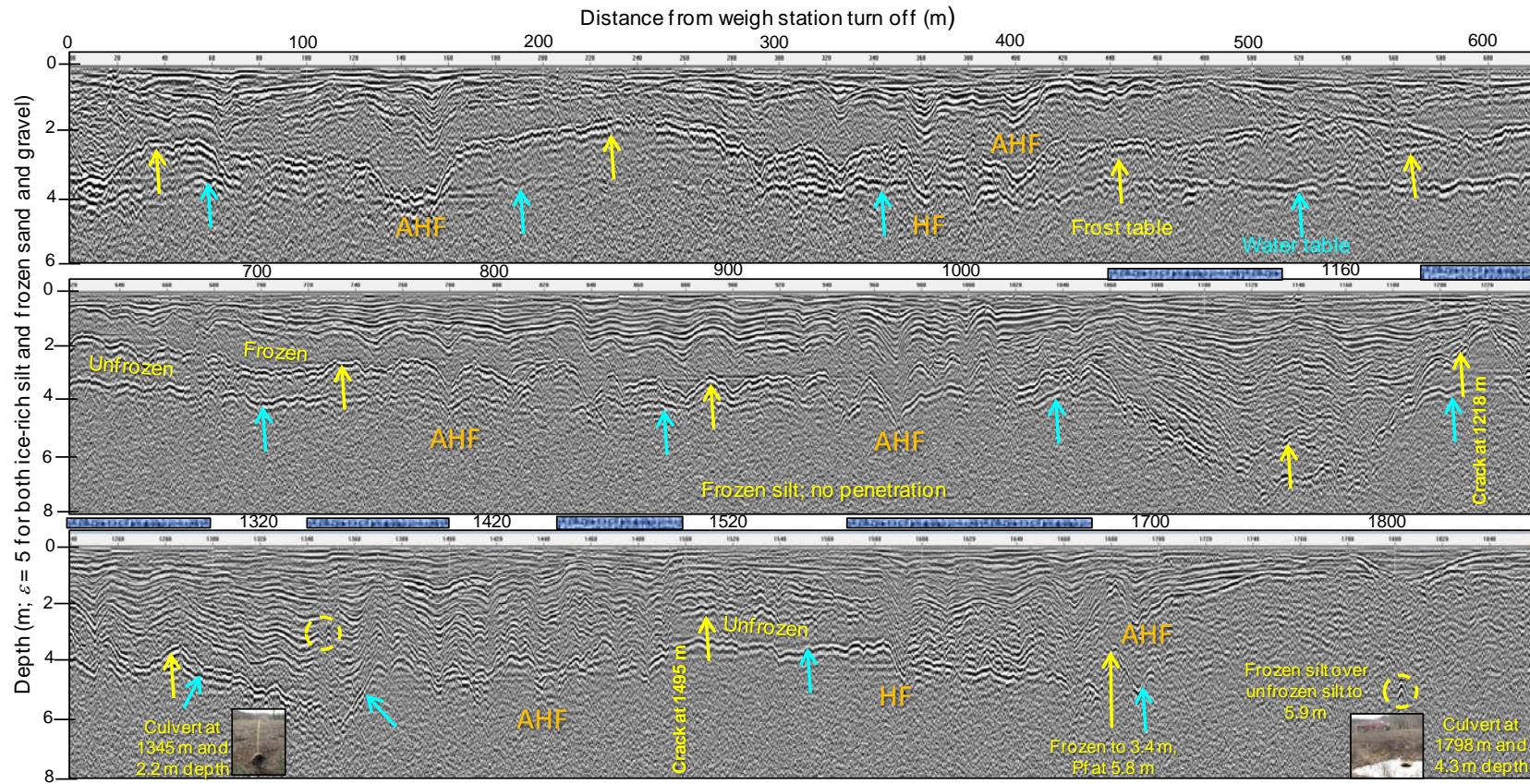


Figure 5 shows the first 1.86 km of the 320 MHz profile, which we recorded on the east-side shoulder going north. This length contains all the interesting thaw settlement features. The 150 MHz profile showed no greater penetration beneath the water table, which means that the underlying material is highly attenuating.

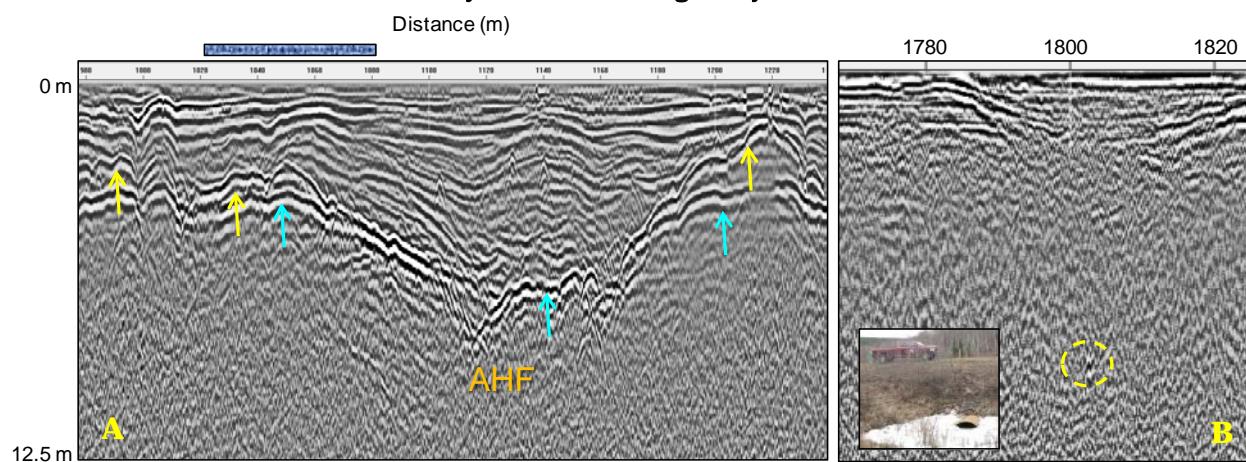
Figure 5. A 320 MHz profile of the first 1860 m of the Elliott Highway, recorded 4 April 2014. The start is at the truck weigh station at Fox. The speckled blue bars show where the road was patched during summer 2014 because of thaw settlement. Yellow arrows indicate the bottom of seasonal frost, and the turquoise arrows indicate the water table. The seasonal frost delineates the fill. HF and AHF labels are below the appropriate folding features, caused by selective thaw settlement above ice deep within the permafrost. The water table often sits right on the permafrost because there is no deeper horizon. There are no hyperbolic diffraction signatures to indicate massive ice. The photos are of the culverts, whose responses are within the dashed circles. The stratigraphic note at the lower left is from borehole records.



The speckled blue bars along the distance scale above each section show where the road was patched during summer 2014 due to thaw settlement. The uppermost horizons are reflections from the stratified sand and gravel fill substrate beneath the pavement. The yellow arrows indicate the bottom of seasonal frost; turquoise arrows indicate the water table. These horizons are recognized by their white–black–white banding, which indicates a horizon between low dielectric material above and high material below. In the seasonal-frost case, this means frozen sand and gravel above thawed silt or sand and gravel. In the water-table case, it means thawed material above saturated material. There is no indication of a further horizon beneath the water table, which would be that of the permafrost surface; and there are no hyperbolic diffraction signatures to indicate massive ice.

The seasonal frost delineates the fill and reaches a maximum depth of about 7 m at a 1140 m distance (Figure 6A). Within this detail, not only does the entire fill section sag but also close examination along the water table and frost depth horizons shows a folded character.

Figure 6. (A) Detail of a deeply frozen section recorded with the larger, 150 MHz antenna unit, showing the inability of lower frequency and 8 $\times$  more power to penetrate any deeper. The underlying material is likely ice-rich loess. AHF indicates anharmonic folding above. (B) Migration for  $\epsilon = 5$  of the culvert (shown in inset) response at 1798 m distance (within dashed circle). The collapse of the hyperbolic diffraction to just a few traces justifies the use of this dielectric constant. The placement of the migrated diffraction shows that our GPS may have been misaligned by about 4 m.



The most interesting features are the wavy horizons, which are pseudo-folds caused by thaw settlement over ice deep within the permafrost. The HF and AHF labels indicate either harmonic folding or anharmonic folding, as explained in Figure 7. Harmonic folds (HF) are concentric, which occurs if the folds are a reaction to only recent sagging so that the fold in the upper few layers projects down through the GPR column (i.e., the fold

at the top affects deeper strata). Layer slippage during compression also causes this. The deeper folding is then just a velocity “pull-down” from recent surficial sagging. Anharmonic folds (AHF) deepen with depth, which means they are old and indicate a long history of settlement. With each episode of road repair, the layers continually deepen and fold. The labels in Figure 5 are below the appropriate folding features.

**Figure 7. The key to interpretation of the presence of massive or concentrated ice. HF shows harmonic folds, in which all folds are concentric. This would occur if the folds are a reaction to only recent sagging so that the fold in the upper few layers projects down through the GPR column. AHF shows anharmonic folds, in which the folds deepen with depth, which means they are old and indicate long progressing settlement.**

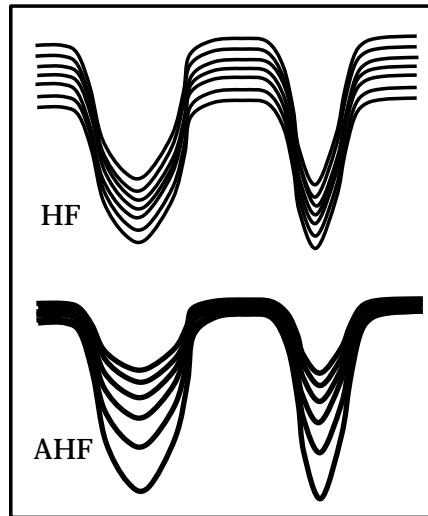


Figure 5 also shows photos of the culverts, whose responses are within the dashed circles; and there also synopsized notes from borehole records. The culvert at 1798 m gave the best response to migration to verify  $\sigma = 5$  (Figure 6B).

Figure 8 shows the OhmMapper capacitive-coupled electrical-resistivity profiles. Consistently, the highest resistivity is at the 1000–1220 m distance, where the deepest gravel fill occurs; at 1250–1500 m, where thaw settlement is indicated by folding; and at 1700–1800 m, where no horizons greater than 1 m suggest high attenuation (e.g., *barely* frozen, such as ice-rich silt, or thaw). At this location, the borehole log at 1752 shows frost to 4.3 m, wet silt to 5.9 m, and then frozen silt.

Figure 9 shows a section where the road is paved over schist bedrock with only marginal sand gravel grading. The schistosity (foliation) of the formation is evident. We calculated a dip of 21° while Péwé listed 30°. The difference is likely due to the angle the road transect makes with the geologic strike. There is no indication of a water or frost table within the schist horizons. However, there are to either side. The Ohm-mapper shows very high resistivity values.

Figure 8. The OhmMapper resistivity profile (2.5 m electrode spacing) along the Elliott Highway. Red to dark red indicates high ice content. The maximum profile depth is 4.6 m, similar to the profile horizons. The highest resistivity is at 1000–1220 m (deepest gravel fill), 1250–1500 m (thaw settlement under folding), and 1700–1800 m where no horizons greater than 1 m suggest high attenuation (e.g., *barely frozen*, such as ice-rich silt, or thaw). A borehole at 1752 shows frost to 4.3 m, wet silt to 5.9 m, then frozen silt, which is consistent with this figure because it shows high resistivity to a 4.6 m depth.

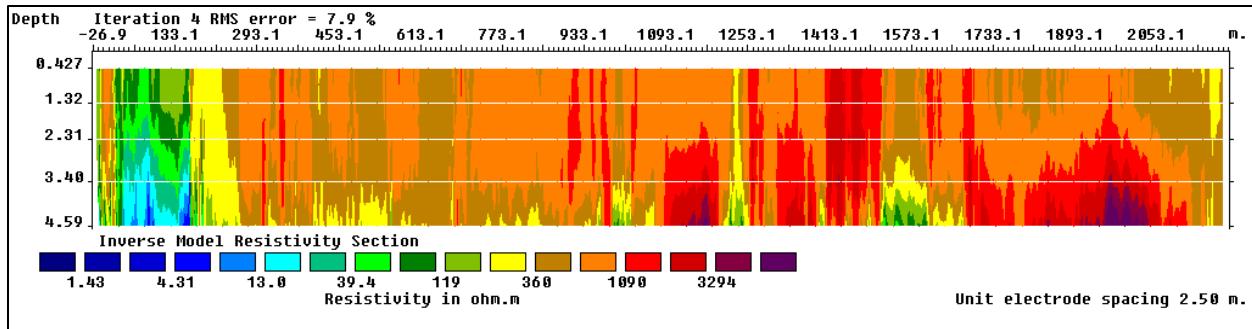
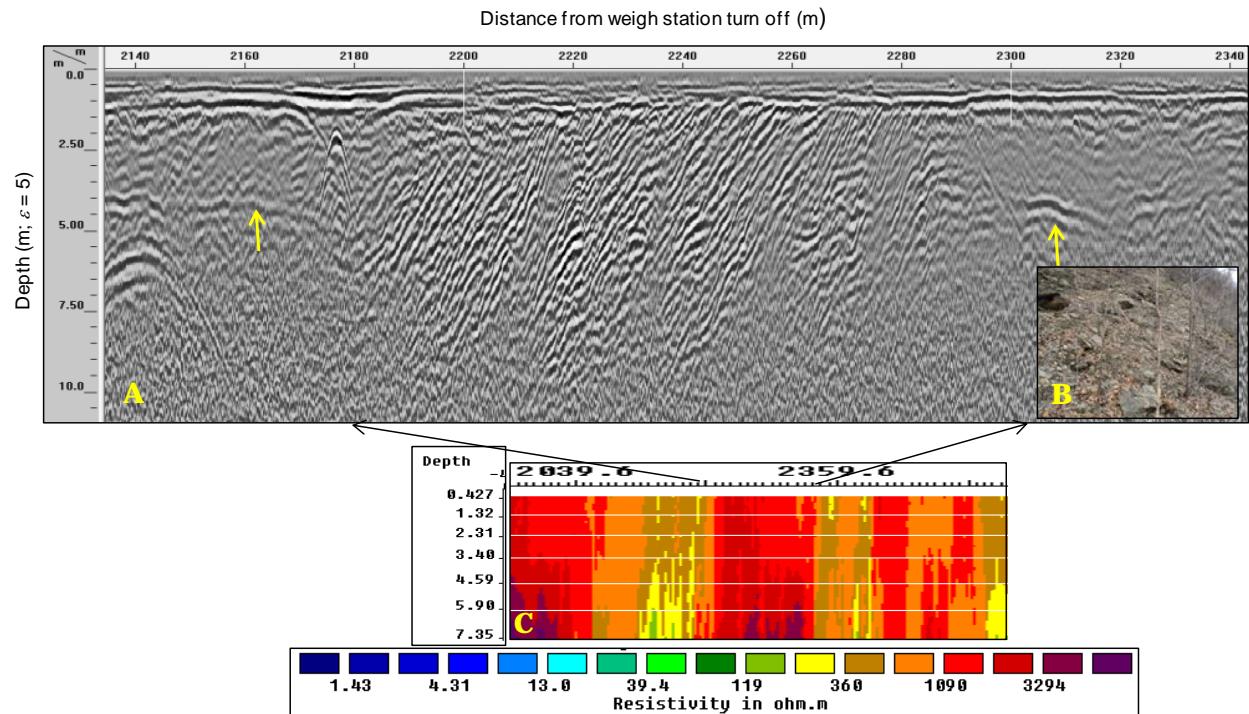


Figure 9. (A) Another 150 MHz GPR section showing about 10 m penetration into the underlying schist. There is no clear frost depth horizon, but there are hints (*arrows*) that it dives deeper within the schist. (B) A photo showing schist exposed above the road from 2200 to 2280 m. The Péwé map (Fig. 4) shows a 30° dip to the south for the schistosity, and with strike (orientation of the dipping planes) across the road. The profile shows 21°. (C) An OhmMapper profile showing high resistivity from 2180 to 2300 m, right over the schist.

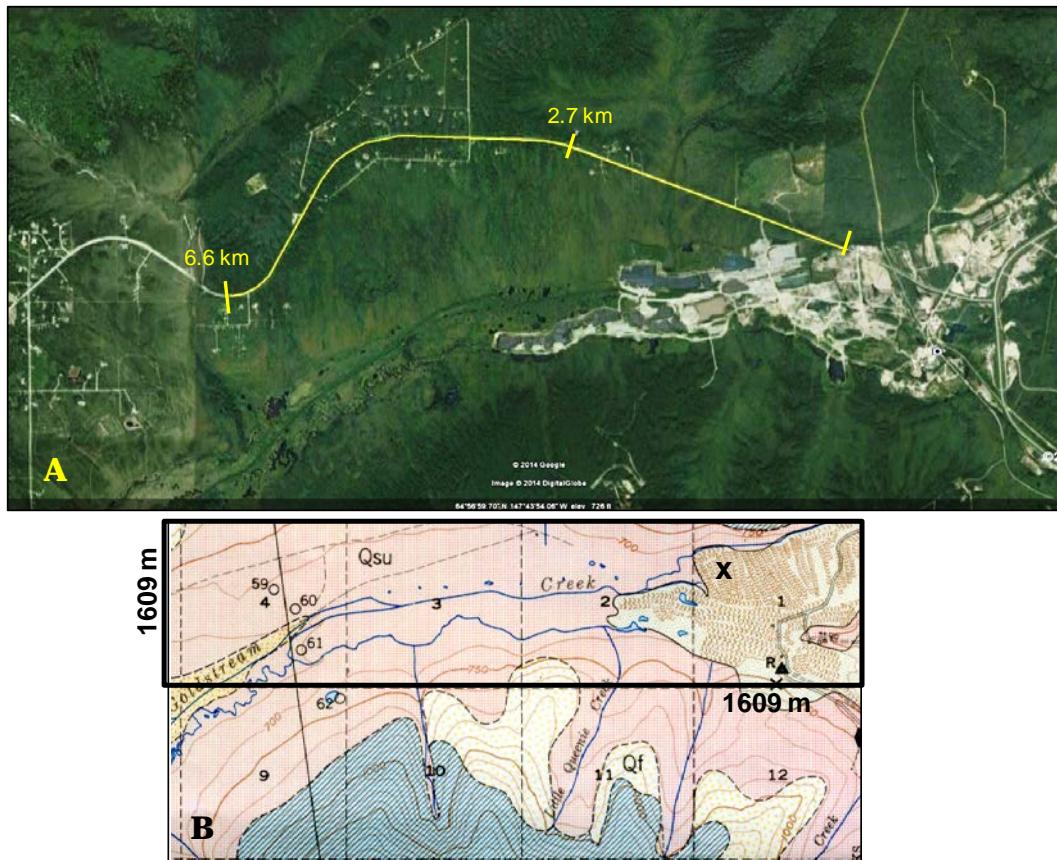


## 4.2 Goldstream Road

This paved road (Figure 10) also lies along a valley. It was mapped by Péwé as having the same silt composition as along the Elliott. The 1958 map does not locate the road but does indicate its approximate location.

The photograph of the antenna unit in Figure 1 was taken at the start of the profiling at the east end 100 m west of the fire station. As with the Elliott, the profile was recorded along the shoulder. We were able to record at only 150 MHz due to the length of the profile and time constraints. We used  $\varepsilon_r = 6$  for our depth calibration, based on conduit diffractions.

Figure 10. (A) 6.6 km of Goldstream Road, starting 100 m past the fire station. The start is approximately at the X mark in the geologic map (B) of Péwé (1958), and the transect is within the rectangular box. Qsu (*pink area*) means undifferentiated quaternary silt.



Figures 11–15 show the most interesting sections and include a feature not seen along the Elliott: a buried remediation surface from repair of old thaw settlement. Both sections in Figure 11 show two prominent horizons, the phases of which indicate the frost depth and water table. The frost depth is at about 1.5 m, which is about 1 m less than along the Elliott. Folding occurs directly below this horizon in both profile panels and so occurs in older sand and gravel fill. Because there is no folding above it, this thaw settlement has been remediated; and there is currently no indication of continued settlement. Consequently, it appears that the frost depth has reached only the depth of the new sand and gravel fill. When the remediation occurred is not known. The folds appear harmonic, which means all

settlement happened concurrently. Close examination of the lower panel near 1320 m shows that the remediated section was initially planed, thus presenting an artificial erosional unconformity.

**Figure 11.** 150 MHz profile sections between 840 and 1440 m along Goldstream Road, recorded 9 April 2014. *Yellow arrows* indicate the frost depth, and *turquoise arrows* indicate the water table. Folds indicate thaw settlement. Old thaw settlement repair (OSR) occurs where folds do not continue to the surface. Conduits (C) are indicated by hyperbolic diffractions.

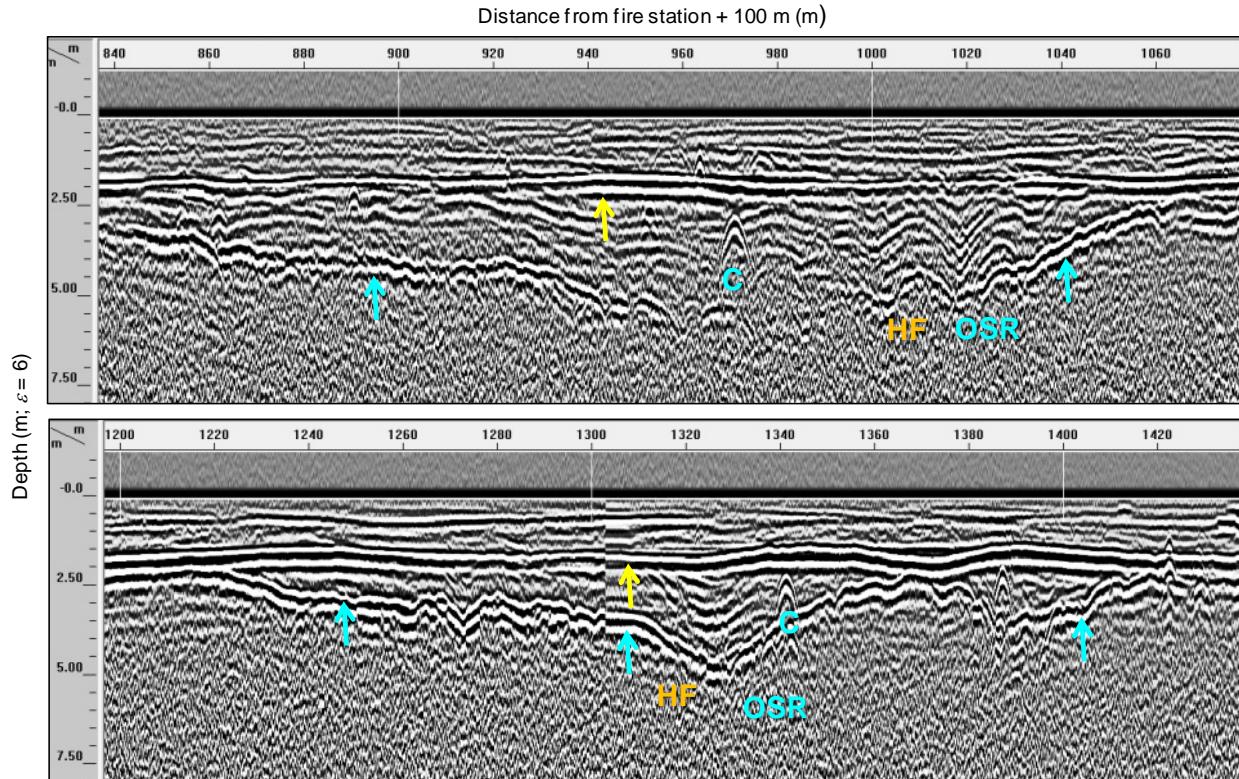


Figure 12 shows two profile panels that exhibit the same phenomenon of remediated settlement. Above the frost depth, there is no folding, while harmonic folds appear below it. As in Figure 11, the water table exceeds 5 m in depth in one spot.

Figure 12. A 150 MHz profile section between 1700 and 2120 m along Goldstream Road, recorded 9 April 2014. Yellow arrows indicate the frost depth, and turquoise arrows indicate the water table. Folds indicate thaw settlement. Old thaw settlement repair (OSR) occurs where folds do not continue to the surface. Conduits (C) are indicated by hyperbolas.

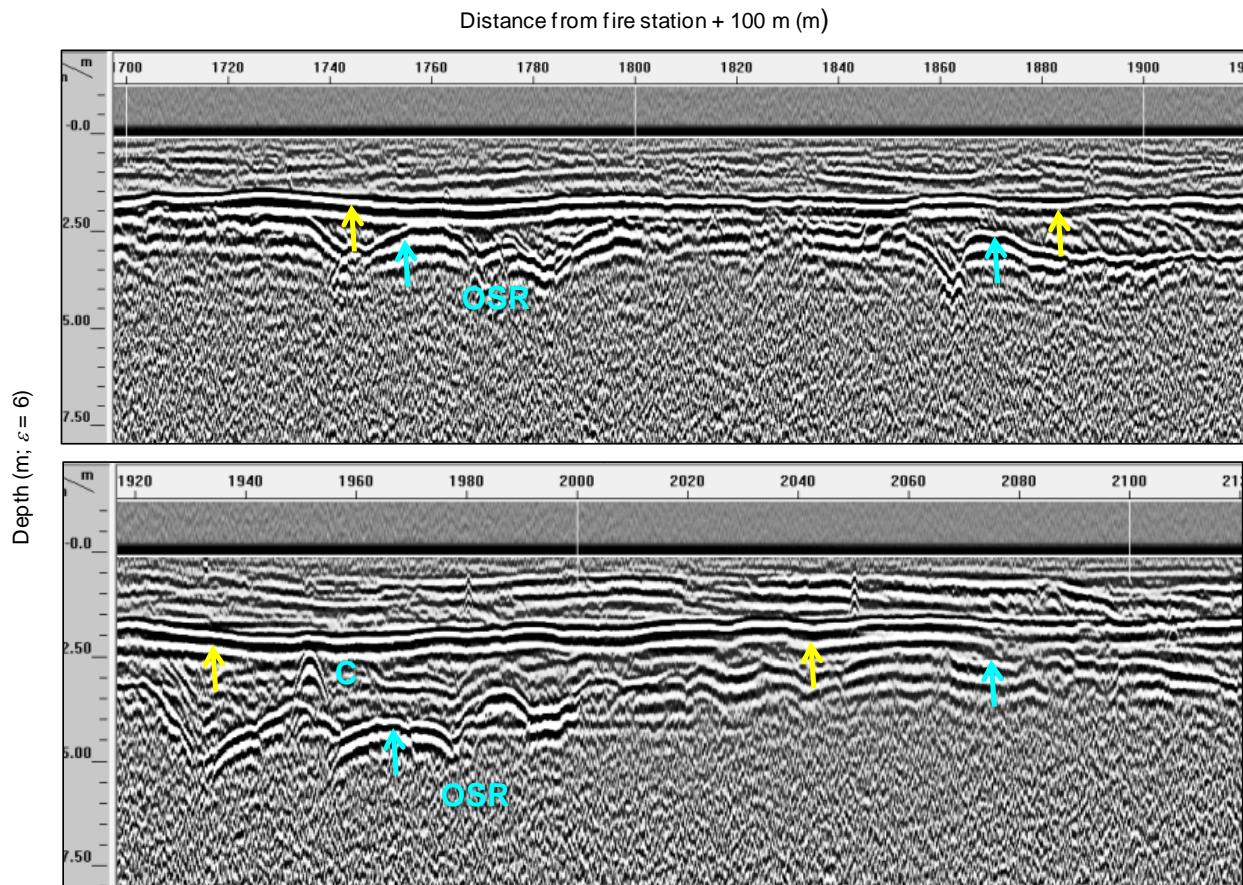
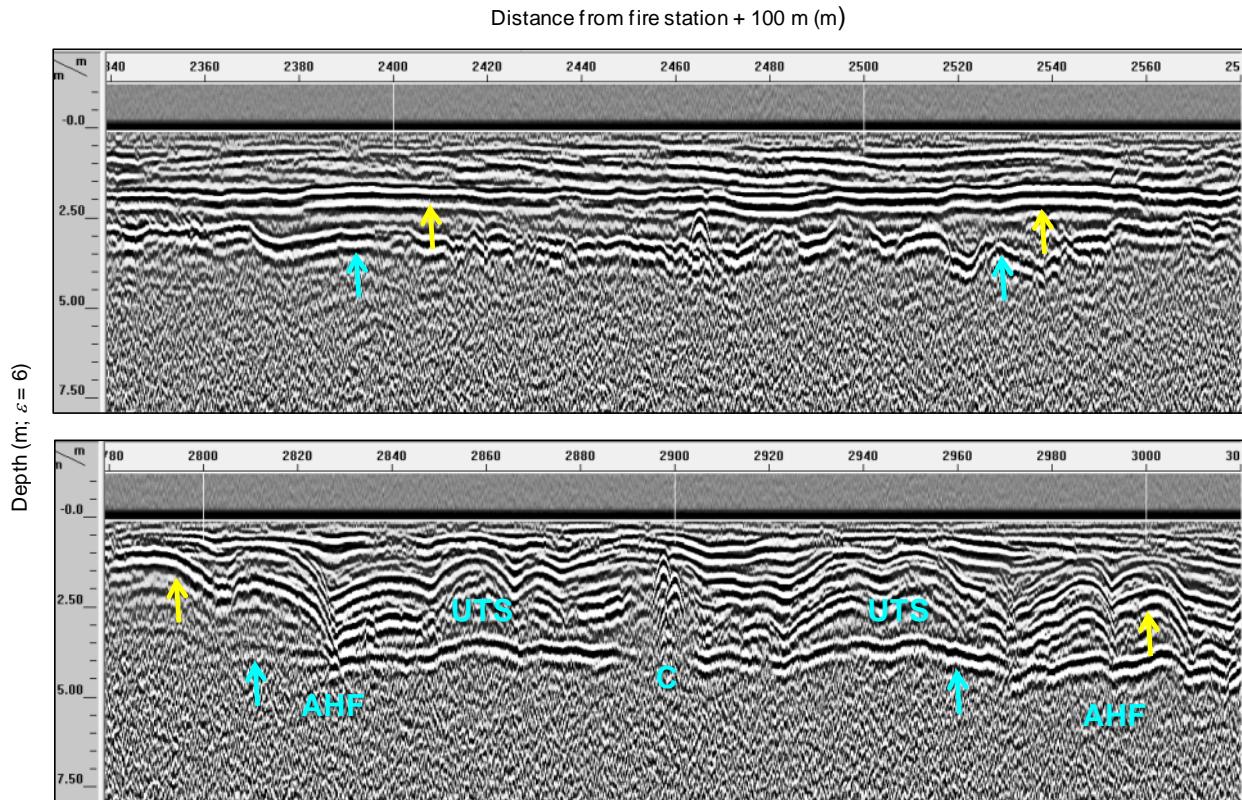


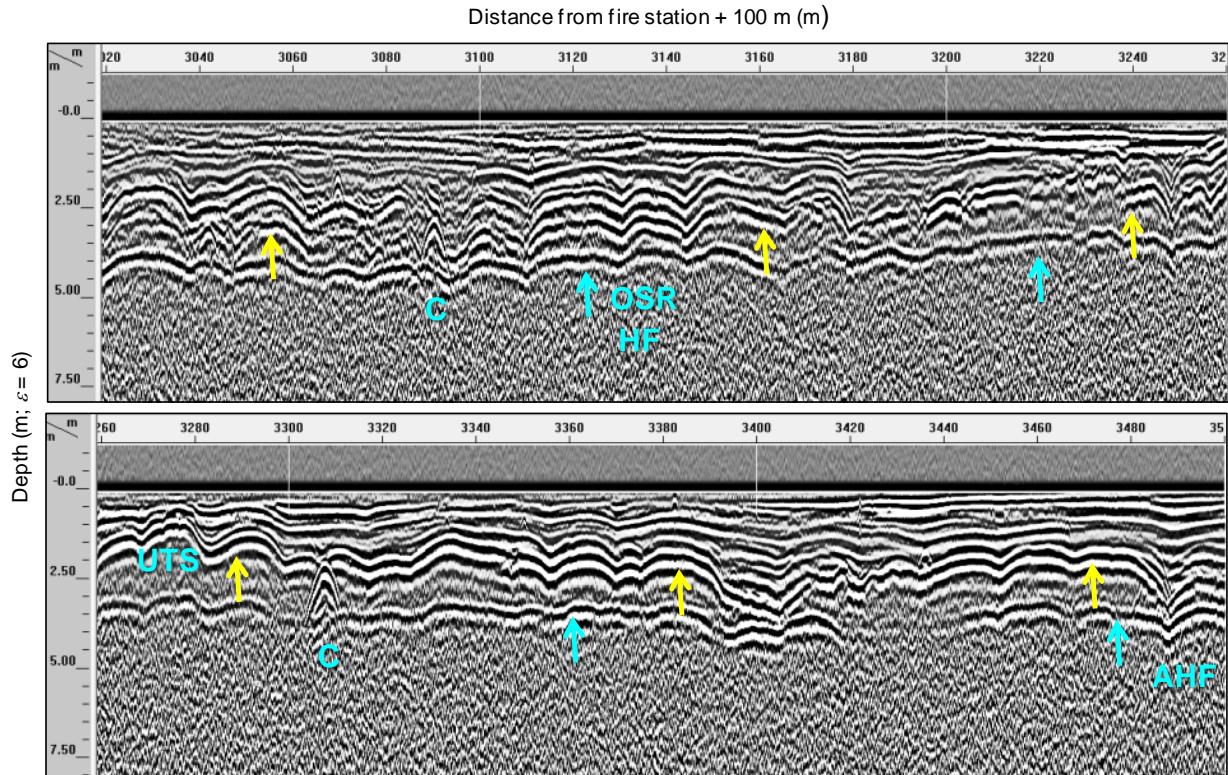
Figure 13 presents two panels with different situations. In the upper panel, the frost depth and water table horizons are evident; but there is little evidence of any thaw settlement. The lower panel, however, shows un-repaired thaw settlement (label UTS) folding that begins near the surface and continues down to the water table. The fold limbs increase with depth, which is an example of anharmonic folding (Figure 7). At 2900 m, there is a cluster of diffractions, which indicates several conduits. Near these diffractions, the water table horizon is not visible. We surmise that this is because of better heat conduction by the conduits.

**Figure 13.** Selected 150 MHz profile sections between 2340 and 3020 m along Goldstream Road, recorded 9 April 2014. *Yellow arrows* indicate the frost depth, and *turquoise arrows* indicate the water table. Folds indicate thaw settlement. Old thaw settlement repair (OSR) occurs where folds do not continue to the surface. Unrepaired thaw settlement (UTS) is indicated by folds that continue to the surface. Conduits (C) or clusters of conduits are indicated by hyperbolas.



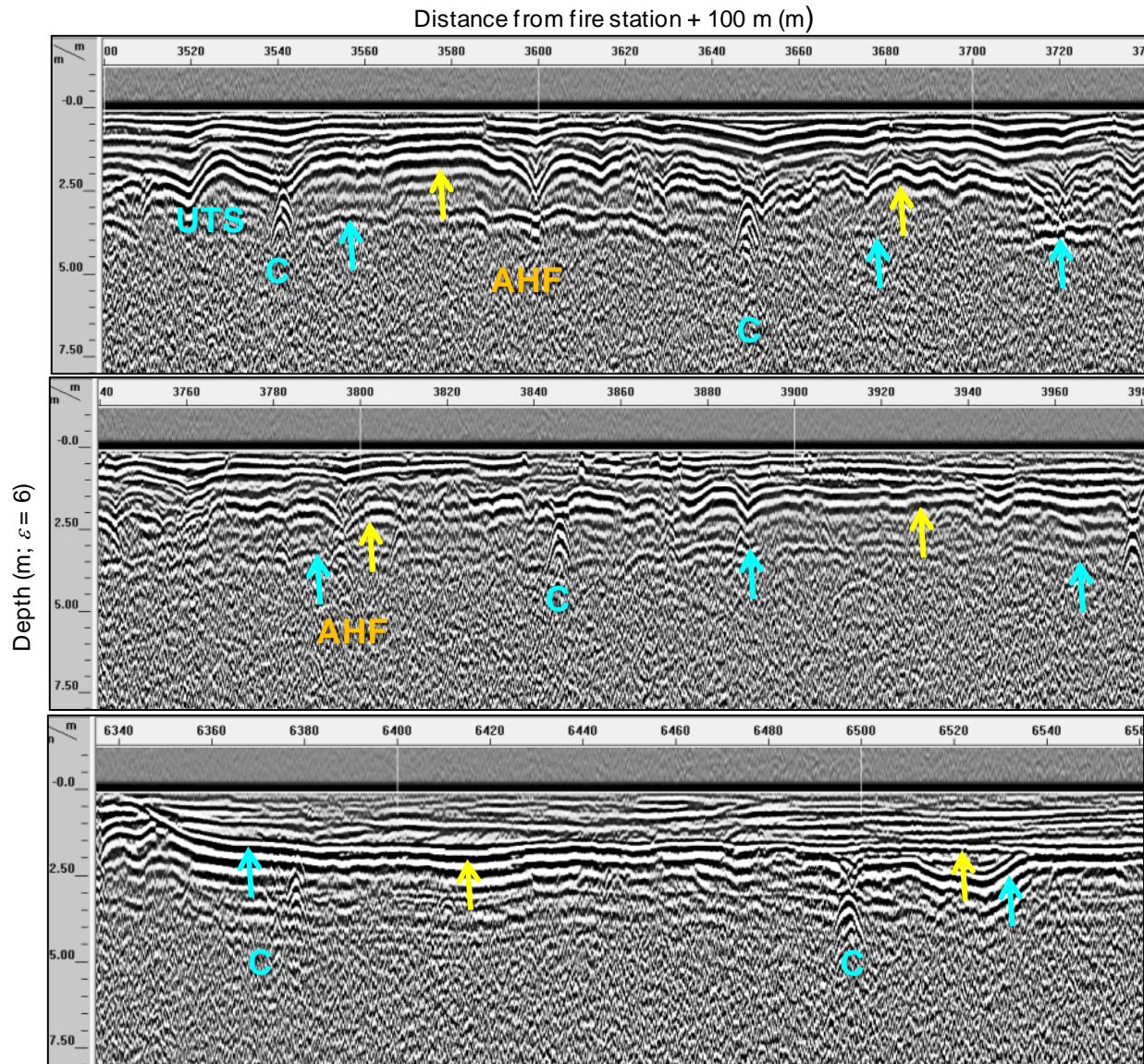
The upper panel of Figure 14 appears to show a hybrid of the previous situations. Here we find thaw settlement that may have been remediated because there is a 1 m layer of unfolded strata above it. However, the frost depth has penetrated as much as 4 m in depth and nearly to the water table. In contrast, the lower panel shows evidence of settlement folding to the surface and no remediation.

Figure 14. Selected 150 MHz profile sections along the first 3.3 km of Goldstream Road, recorded 9 April 2014. Yellow arrows indicate the frost depth, and turquoise arrows indicate the water table. Folds indicate thaw settlement. Old thaw settlement repair (OSR) occurs where folds do not continue to the surface. Unrepaired thaw settlement (UTS) is indicated by folds that continue to the surface. Conduits (C) or clusters of conduits are indicated by hyperbolas.



The upper panel of Figure 15 shows the best example of anharmonic folding, which is centered at 3600 m. The dip is severe enough to cause a secondary diffraction that interferes with the water table horizon. From 3640 to 3710 m, the water table is hardly visible, which indicates wet silt. The central panel also shows a strong dip, anharmonic folding, and a diffraction artifact, all centered at 3795 m. After 3900 m, there is no indication of thaw settlement; and a shallow water table reaches about 3 m in depth at most. The lower panel shows a typical section.

Figure 15. Selected 150 MHz profile sections along the first 3.3 km of Goldstream Road, recorded 9 April 2014. Yellow arrows indicate the frost depth, and turquoise arrows indicate the water table. Folds indicate thaw settlement. Old thaw settlement repair (OSR) occurs where folds do not continue to the surface. Unrepaired thaw settlement (UTS) is indicated by folds that continue to the surface. Conduits (C) or clusters of conduits are indicated by hyperbolas. The lower profile shows contact of the water table to the frozen layer.



#### 4.3 Tok Cutoff Road

Although these profiles were recorded 20 March 1998, we discuss them because they are the only example where buried ice was encountered within a natural deposit of sand and gravel. The site is near Mile 62 (100 km) along the Tok Cutoff Road that runs northeast from Glenallen to Tok Junction (Figure 16). The particular section that we profiled was cut into a glacial moraine that likely emanated from Mt. Wrangle, the peak of which

is about 75.6 km to the south. Consequently, limited stratification should be expected. The nearest present glacier is about 43.4 km away. When the cut was made (estimated 1990–1997), the road crew encountered blue ice that appeared to be of glacial origin. An unknown thickness of insulating layer of Styrofoam was placed on the ice, and the cut was refilled to a 5 m thickness. At the time we surveyed, the road was uneven with obvious thaw settlement. Today (Figure 16), there are numerous patches in this area, showing that the thaw settlement has continued.

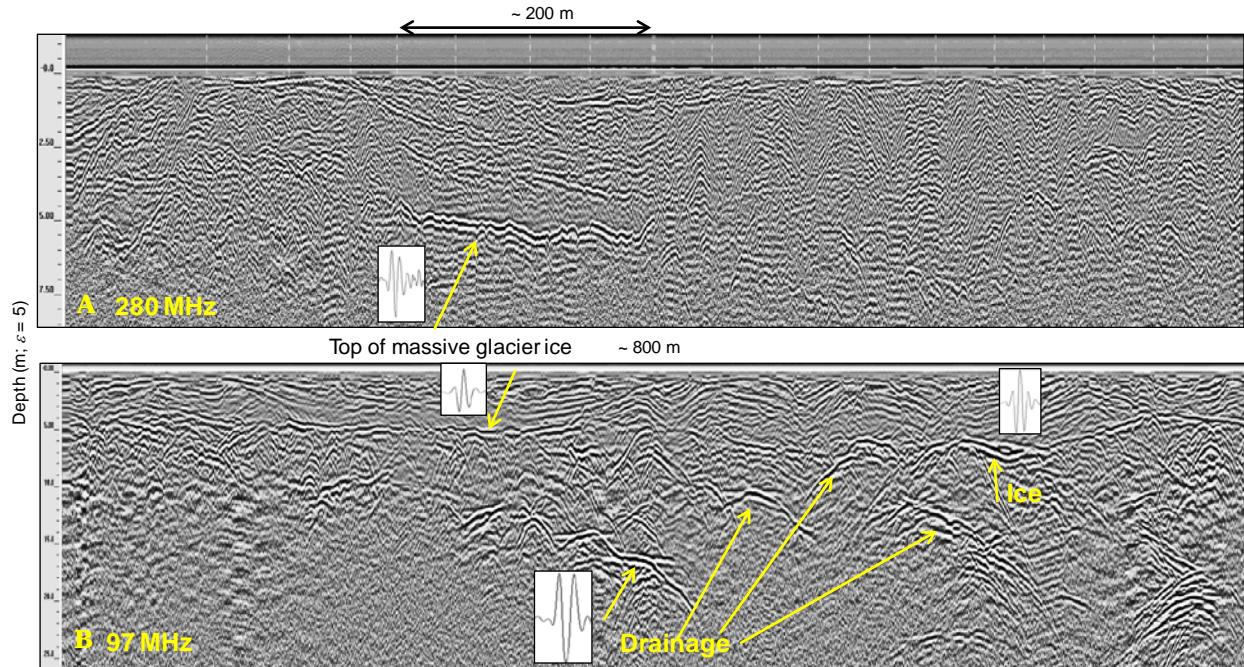
**Figure 16.** (A) An image from 9 April 2013 of the section of Tok Highway that has been repeatedly repaired since at least 1997. Arrows indicate black patches where thaw settlement has been repaired. (B) Detail of the area (indicated by red arrow in A) discussed in this report.



Figure 17A shows a 280 MHz profile recorded with the “400 MHz” antenna. The arrow indicates the ice/insulating board response. The polarity of reflected pulse is + – + (white–black–white banding), which indicates a low over high dielectric contrast. This polarity sequence is consistent with the Blue Board insulation being thick enough to present a layer of air over the ice. The rest of the profile comprises mainly diffractions, as would be expected of till.

Figure 17B shows a 97 MHz profile recorded with a prototype to the Model 5106A. In this case, the insulating board is not thick enough to present the same dielectric contrasts; and so the ice horizon has the opposite half-cycle – + – (black–white–black banding) polarity sequence (left and right inserts) to indicate a relatively higher (wet sand and gravel) material over a relatively lower one (ice). In strong contrast are the waveforms associated with horizons that descend from the massive ice. These exhibit + – + (white–black–white banding), which, along with their intensity, can only indicate water.

Figure 17. (A) A 280 MHz profile of Tok Cutoff Road recorded 20 March 1998 over an area of thaw settlement, shown in Fig. 5 (red arrow). A layer of insulating Styrofoam (Blue Board) sits atop this ice, which makes the reflection waveform white–black–white (insert; arrows points to where it occurs) as if it came from a wet surface. (B) A 97 MHz profile of same section showing complicated massive ice and melting. The massive ice in (B) now has a black–white–black band (left waveform insert), which is correct for solid ice under frozen sand and gravel and Blue Board too thin to change the waveform polarity. A massive ice horizon also occurs at the far right. The strong white–black–white banded horizons at the center (center insert) are likely meltwater draining off this massive ice.



#### 4.4 Old Steese Highway

Figure 18 shows a residential section transected by the Old Steese Highway. It is located within the loess deposits mapped by Péwé (1958). We recorded our 150 MHz profile (Figure 19) between Springwater and McGrath Roads on 9 August 2013. By this time of year, seasonal frost should be gone.

The profile shows only one consistent horizon, which is at about a 3.5 m depth. The black–white–black banding of this horizon means that it is a response to an interface between a relatively higher dielectric medium above and a relative lower one below. The medium above is unfrozen sand and gravel, which is well drained because its  $\epsilon_r = 7.8$ , an average obtained from the diffraction responses to several conduits and indicative of about 15% volumetric water content, assuming a volumetric felsic mineral content of 0.52. The medium below is either frozen or dry, the latter of which is unlikely because of drainage. Therefore, we think it is permafrost because the profile also shows discrete sections of folded strata within thaw

settlement. Only Little Fox Road lies within one of these sections; the other roads do not. The folding is severe and anharmonic, meaning that the settlement has progressed for many years. The medium below is also not likely to be seasonal frost or else a second reflection from either a water table or from permafrost would appear.

Figure 18. (A) A section of the Old Steese Highway going N-S profiled August 2013. The distance from Springwater to Little Fox is 250 m and 1350 m to McGrath Road. The section lies entirely within the pink Qsu (Quaternary undifferentiated silt) unit of Péwé (1958) that resides within the box in (B).

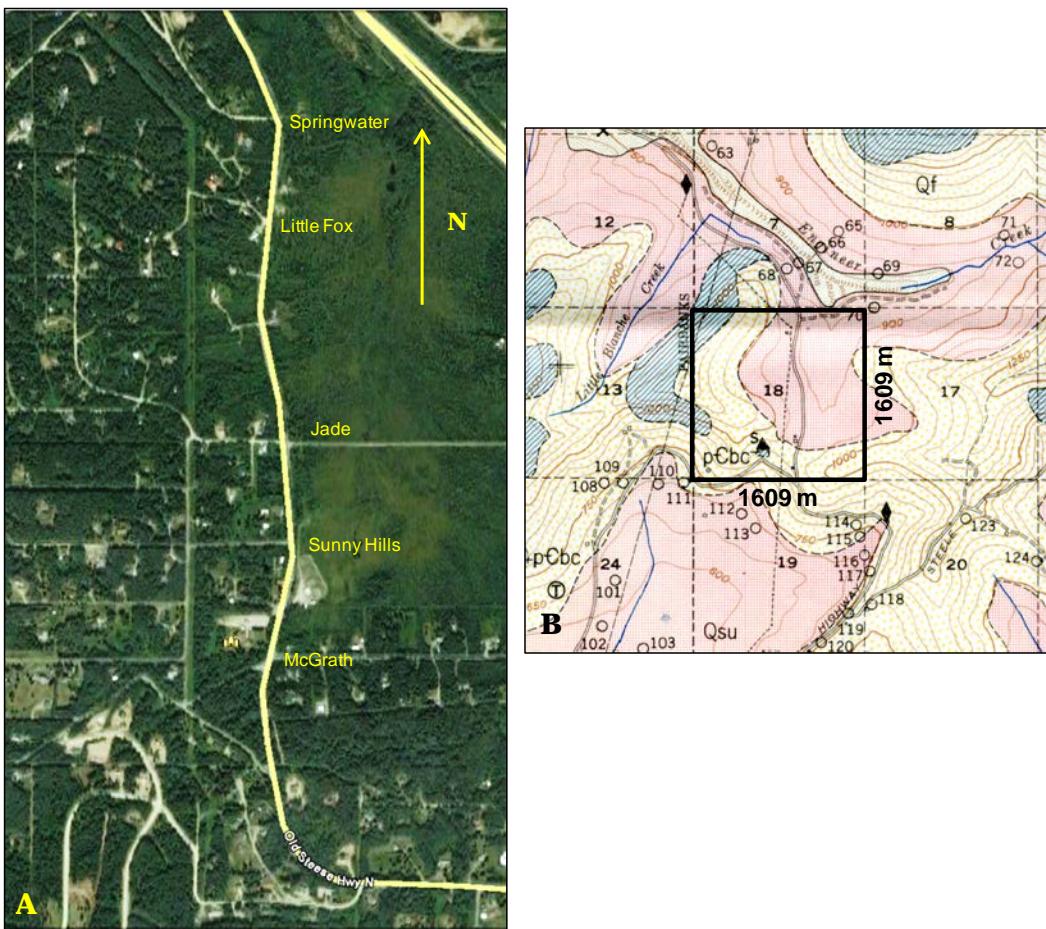
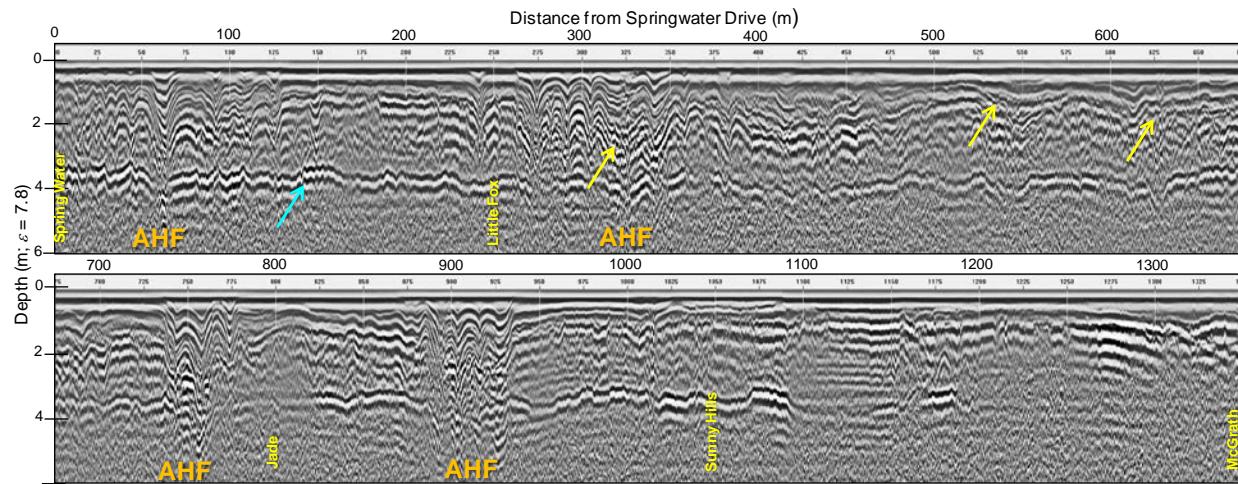


Figure 19. A 150 MHz profile of a section of the Old Steese Highway going N-S and recorded 9 August 2013.

The black–white–black horizon (*turquoise arrow*) means thaw over frozen. The  $\epsilon = 7.8$  is the average for several conduit diffractions (*yellow arrows* at 325, 545, and 628 m), which are not discernible because of the horizontal compression used for display, and indicates well-drained sands and gravel. Diffractions generated within the nadir of a dip were not considered for interpretation of relative dielectric permittivity.



## 5 Discussion and Conclusions

Two important questions emerge from our analyses. First, why is thaw settlement selective (i.e., why are there folds instead of one big sag)? The results from Tok suggest that drainage occurs along selective pathways, in which case thaw occurs irregularly along either massive ice surfaces or within sections of segregated ice. The uninsulated ice surface at Tok in Figure 17B is irregular. All of the sections show that the folds are not evenly spaced. As ice melts, the water infiltrates the surrounding sediments and refreezes, thus producing additional irregularity.

The second question is why is there no penetration into the frozen silt as there is within sands and gravels? We think that because the silt is not deeply frozen, there is adsorbed water on the silt and clay particle surfaces. This dispersed water causes Maxwell-Wagner relaxation (Arcane and Boatnott 2012), whereby discrete pockets of conductive material act as macrodipoles that cannot stay in phase with the applied field. Consequently, wave energy is converted into heat and conductive currents. Although the relaxation is generally centered between 1 and 20 MHz, the relaxation is broadband and affects the GPR frequency range. In addition, in Fairbanks silt there is much clay mineral content (Arcane et al. 2008), including montmorillonite (which can retain unfrozen water).

We conclude that folding diagnoses thaw settlement but not of the specific type of ice that exists within the permafrost. The high attenuation of the silt matrix prevents GPR imaging of permafrost and identification of the existence of massive or segregated ice. Regardless of the type of ice, GPR is an effective tool for highway maintenance in permafrost areas as long as there are strata that can experience folding. It can also be useful for planning in areas of sands and gravels where penetration can exceed 10 m and ice layers or meltwater can easily be detected.

## References

Annan, A. P., and J. L. Davis. 1976. Impulse radar sounding in permafrost. *Radio Science* 11:383–394.

Arcone, S. A., and G. Boitnott. 2012. Maxwell-Wagner relaxation in common minerals and a desert soil at low water contents. *Journal of Applied Geophysics* 81(June): 97–105.

Arcone, S. A., and A. J. Delaney. 1982. Dielectric properties of thawed active layers overlying permafrost using radar at VHF. *Radio Science* 17:618–626.

Arcone, S. A., E. F. Chacho, Jr., and A. J. Delaney. 1992. Short-pulse radar detection of groundwater in the Sagavanirktok River floodplain in early spring. *Water Resources Research* 28(11):2925–2936.

Arcone, S. A., D. E. Lawson, A. J. Delaney, J. C. Strasser, and J. D. Strasser. 1998. Ground-penetrating radar reflection profiling of groundwater and bedrock in an area of discontinuous permafrost. *Geophysics* 63(5):1573–1584.

Arcone, S. A., M. L. Prentice, and A. J. Delaney. 2002. Stratigraphic profiling with ground-penetrating radar in permafrost: A review of possible analogs for Mars. *Journal of Geophysical Research* 107(E11). doi: 10.1029/2002JE001906.

Arcone, S. A., S. A. Grant, G. Boitnott, and B. Bostick. 2008. Complex permittivity and clay mineralogy of grain-size fractions in a wet silt soil. *Geophysics* 73(3):J1–J13.

Bertram, C. L., K. J. Campbell, and S. S. Sandler. 1972. Locating large masses of ground ice with an impulse radar system. In *Proceedings of the Eighth International Symposium on Remote Sensing of Environment, 2–6 October*. Ann Arbor, MI: University of Michigan.

Brandt, O., K. Langley, J. Kohler, and S. Hamran. 2007. Detection of buried ice and sediment layers in permafrost using multi-frequency ground penetrating radar: A case examination on Svalbard. *Remote Sensing Environment* 111:212–227.

Davis, J. L., W. J. Scott, R. M. Morey, and A. P. Annan. 1976. Impulse radar experiments on permafrost near Tuktoyaktuk, Northwest Territories. *Canadian Journal of Earth Science* 13:1584–1590.

Delaney, A. J., S. A. Arcone, and E. F. Chacho, Jr. 1990. Winter short-pulse radar studies on the Tanana River. *Arctic* 43(4): 244–250.

Gacitua, G., M. P. Tamstorf, and L. Slater. 2010. Using ground-penetrating radar to estimate active layer moisture conditions in the Arctic. In *Proceedings of the 13th International Conference on Ground Penetrating Radar, 21–25 June, Lecce, Italy*.

Moorman, B. J., S. D. Robinson, and M. M. Burgess. 2003. Imaging periglacial conditions with ground-penetrating radar. *Permafrost and Periglacial Processes* 14:319–329.

Péwé, T. L.. 1958. *Geologic map of the Fairbanks (D-2) Quadrangle*. Scale 1:63,360. U.S. Geological Survey.

Pilon, J. A., M. Allard, and M. K. Séquin. 1992. Ground probing radar in the investigation of permafrost and subsurface characteristics of surficial deposits in Kangiqsualujuaq, northern Quebec. In *Ground Penetrating Radar*, ed. J. A. Pilon, 165–175. Geological Survey of Canada Paper 90-4. Ottawa, Canada: Canada Communication Group.

# REPORT DOCUMENTATION PAGE

*Form Approved  
OMB No. 0704-0188*

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. **PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.**

<b>1. REPORT DATE (DD-MM-YYYY)</b> August 2016		<b>2. REPORT TYPE</b> Technical Report/Final		<b>3. DATES COVERED (From - To)</b>	
<b>4. TITLE AND SUBTITLE</b>  Ground-Penetrating-Radar Profiles of Interior Alaska Highways: Interpretation of Stratified Fill, Frost Depths, Water Table, and Thaw Settlement over Ice-Rich Permafrost				<b>5a. CONTRACT NUMBER</b>	
				<b>5b. GRANT NUMBER</b>	
				<b>5c. PROGRAM ELEMENT NUMBER</b>	
<b>6. AUTHOR(S)</b>  Steven A. Arcone and Kevin Bjella				<b>5d. PROJECT NUMBER</b>	
				<b>5e. TASK NUMBER</b>	
				<b>5f. WORK UNIT NUMBER</b>	
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b>  U.S. Army Engineer Research and Development Center (ERDC) Cold Regions Research and Engineering Laboratory (CRREL) 72 Lyme Road Hanover, NH 03755-1290				<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>  ERDC/CRREL TR-16-14	
<b>9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b>  The ERDC Director's Office 3909 Halls Ferry Road Vicksburg, MS 39180-6199				<b>10. SPONSOR/MONITOR'S ACRONYM(S)</b> ERDC	
				<b>11. SPONSOR/MONITOR'S REPORT NUMBER(S)</b>	
<b>12. DISTRIBUTION / AVAILABILITY STATEMENT</b> Approved for public release; distribution is unlimited.					
<b>13. SUPPLEMENTARY NOTES</b> ERDC Center-Directed Research, "Integrated Technologies for Delineating Permafrost and Ground-State Conditions"					
<b>14. ABSTRACT</b> In early spring 2014, we recorded ground-penetrating-radar (GPR) profiles along several highways in interior Alaska to determine present and potential damaging thaw settlement, which could help site and design infrastructure in permafrost terrains. We used GPR pulses centered near 100, 150, and 320 MHz. Comparative profiles of electrical resistivity, historical GPR profiles, and limited borehole information aided interpretations. Beneath the Elliott Highway, Goldstream Road, and the Old Steese Highway, construction fill was recognized by its stratification; and frost depth and water-table horizons were recognized by phase attributes of the reflected pulse, as dictated by dielectric permittivity contrasts, relative depths, and continuity. Undulating fill stratification indicated thaw settlement, caused by melting of buried ice. We interpreted various stratigraphic folds to represent cases of active, recent, remediated and historical settlement. A section along the Tok Cutoff Road revealed the top and bottom of massive ice within glacial moraine. Signal penetration was greatly reduced beneath the water table, and the permafrost table was not detected. This information is valuable for highway maintenance and planning of new construction, especially in remote locations where information on permafrost and ice features are limited.					
<b>15. SUBJECT TERMS</b> Ground penetrating radar, Ice--Alaska, Permafrost, Roads--Alaska, Roads--Design and construction, Thaw settlement					
<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT</b> SAR	<b>18. NUMBER OF PAGES</b> 36	<b>19a. NAME OF RESPONSIBLE PERSON</b>
<b>a. REPORT</b> Unclassified	<b>b. ABSTRACT</b> Unclassified	<b>c. THIS PAGE</b> Unclassified			<b>19b. TELEPHONE NUMBER (include area code)</b>